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FLAT PLATE SKIN FRICTION IN LOW DENSITY HYPERSONIC FLOW—PRELIMINARY RESULTS

E. S. MOULIC
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA

FEBRUARY 1963

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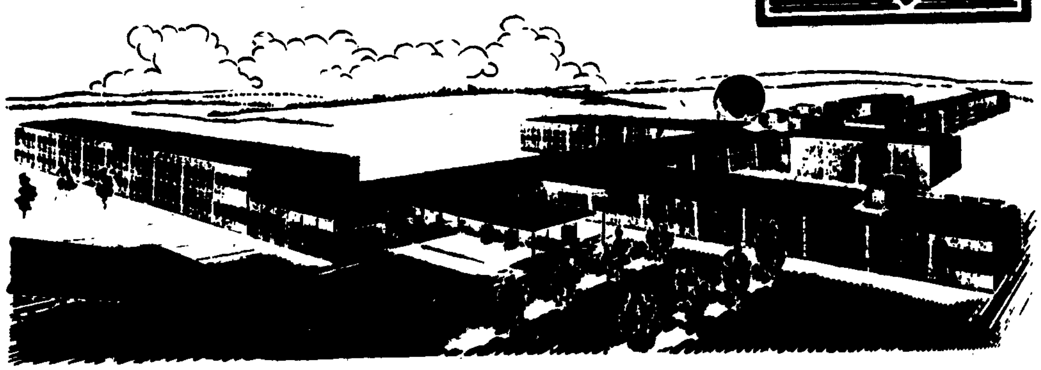

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Experimental local skin friction data were obtained for the strong interaction region of a sharp edged adiabatic flat plate model over the flow parameter ranges 5.5 < M < 6.0, 150 < Re_x < 400, 9.8 < $\bar{X}$ < 13.0. These data, the results of the first trials of a complex experimental apparatus, yield local skin friction coefficients significantly below the predictions of strong interaction theory.

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CONTRACT AF 33(657)-8607
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OFFICE OF AEROSPACE RESEARCH
UNITED STATES AIR FORCE
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FOREWORD

This report was prepared at the Institute of Engineering Research, University of California, Berkeley, California, under Contract AF 33(657)-8607, Project 7064, "Aerothermodynamic Investigations in High Speed Flow," Task 7064-01, "Research on Hypersonic Flow Phenomena." The work was administered under the direction of the Aeronautical Research Laboratories, Office of Aerospace Research, USAF, with Capt. Walter W. Wells as Task Scientist.

The theoretical analysis and experimental work were carried out by E. S. Moulic under the supervision of Professors G. J. Maslach, S. A. Schaaf, and W. H. Giedt.

ABSTRACT

Experimental local skin friction data were obtained for the strong interaction region of a sharp edged adiabatic flat plate model over the flow parameter ranges $5.5 < M < 6.0$, $150 < Re_x < 400$, $9.8 < \overline{X} < 13.0$. These data, the results of the first trials of a complex experimental apparatus, yield local skin friction coefficients significantly below the predictions of strong interaction theory.

TABLE OF CONTENTS

LIST OF FIGURES

I. INTRODUCTION

For the past several years a portion of the research effort of the Rarefied Gas Dynamics Project of the Aeronautical Sciences Laboratory has been directed toward clarification of the boundary layer phenomena observed on a flat plate model in a supersonic low density test stream. Schaaf and Sherman[1] measured drag on short flat plates up to a Mach number of 4, and later Tellep and Talbot[2] investigated lift on similar models for the same flow conditions. In order to gain a better understanding of the flow near the leading edge Laurmann[3] explored this region with a free molecule probe for Mach numbers of 2 and 4. Later Schaaf, Hurlbut, Talbot and Aroesty[4] measured the induced pressures on flat plates in low density hypersonic flows. These last experiments revealed enough disagreement with interaction boundary layer theories to generate a desire for more induced pressure data at higher values of the hypersonic interaction parameter, $\bar{X} = M_\infty^3 \sqrt{\frac{C_\infty}{Re_x}}$, but dimensional limitations in the model and test stream development problems prevented any immediate prospects for a significant extension of the data. Since the laboratory group involved with the No. 4 Low Density Wind Tunnel had recently gained considerable experience with wind tunnel force measuring apparatus[5,6] it was decided to study the possibility of using a floating element system to make local skin friction measurements close to the leading edge of a flat plate. The specific motivation for these new experiments was a desire to clarify the importance of the slip boundary condition and to further clarify the regions of application of hypersonic interaction boundary layer theories for adiabatic wall conditions.

Preliminary analysis of the proposed experimental technique revealed several areas of severe difficulty. The strong skin friction gradient near

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the leading edge of the model required a floating element which was short in the axial direction, and this in turn reduced the predicted forces to a value smaller than could be measured satisfactorily with the existing wind tunnel balances, thus necessitating the construction of a new, more sensitive force measuring system. Exploratory testing with the existing laboratory balances operating at their maximum sensitivities indicated that a more sensitive balance would be difficult to operate in a wind tunnel environment which included vibrations and small structural level changes. In addition, the high sensitivity balance would be readily affected by small extraneous air currents and would be difficult to operate within the range of the extremely small movements allowed the floating element. The construction of the model presented another area of severe difficulty, since the small size of the floating element and its proximity to the sharp leading edge of the flat plate required high precision and tedious miniaturization. Analysis of tl operational characteristics of the model indicated that the pressure in the cavity surrounding the floating element would influence the measured forces and that the alignment of the element to the plane of the model surface would be a difficult instrumentation problem.

Since the performance of the force measuring system was crucial to the success of the proposed experiments, it seemed advisable to distort the objective of the construction program and the first experiment toward perfection of the balance techniques and to limit the model to a single simple configuration. The following pages describe briefly the apparatus and the preliminary reults, but analysis of the data is not attempted since the major effort is still being directed toward obtaining more extensive and reliable data.

II. APPARATUS

The operating principle of the balances used with the Low Density Wind Tunnels has been adequately described elsewhere.[7] In essence, they are a one-component beam balance which uses a crossed strip flexure pivot, a Schaevitz linear variable differential transformer (LVDT) for sensing null, and a quartz extension spring for absorbing the reaction of the aerodynamic force. Figure 1 is a schematic diagram of the system. The microbalance used for this experimental program was constructed specifically for shear stress measurements and represents a considerable refinement of the earlier balances. The design objectives were: 1) maximum sensitivity but retention of the robust nature of the beam system so that handling and model mounting difficulties would be minimized, 2) maximum utilization of existing auxiliary equipment such as null indication circuitry, spring extension controls, power supplies, etc., 3) versatility so it could be readily adapted to future experimental needs.

In general, all of the design objectives were satisfied by the following features: 1) the torsional spring constant of the flexure pivot was reduced by using smaller flexure strips, 2) the uniformity of the torsional spring constant of the flexure pivot was improved by more uniform clamping of the steel strips and by more careful assembly methods, 3) the sensitivity of the null indicator was increased by raising the excitation voltage and frequency of the LVDT, 4) the least count of the quartz spring extension mechanism was decreased by a factor of 10 and the backlash in the extension mechanism was considerably reduced, 5) the available range and ease of adjustment of the eddy current damping was improved by better magnet designs, 6) the effect of stray air currents was removed by housing the balance in a sealed case and moving all heat sources such as electric motors to the outside of the case.

Extensive experience with the completed microbalance shows the design objectives were satisfactorily accomplished. No attempts have been made to determine its maximum sensitivity, but it operates easily with about two orders of magnitude more sensitivity than its predecessors. A least count of 5 micrograms can be readily obtained. Based on strong interaction theory the smallest forces expected for the shear stress experiments are about one milligram, so the microbalance should be more than adequate for the experiments at hand. The robust nature of the older balances has been preserved, but its ease of operation is reduced by the confinement of its case.

The flat plate model used for these experiments was constructed with a sharp leading edge (Reynolds number based on leading edge thickness about equal to one) and a 20° underside. A small floating element fits in a long narrow cavity 0.037" downstream from the tip of the plate and is suspended by a simple but carefully constructed mechanism which is entirely internal to the model and balance case and is accessible through various plate covers, two of which are on the upper surface of the flat plate. The floating element is provided with 0.002" clearance at its sides and bottom and its upper surface is aligned to the surface of the flat plate by manipulating adjustments in the element suspension system, and by moving the plate with respect to the element. The ability of a stereo microscope to enhance the depth perception of the observer was used to control this alignment to within ±0.0005 for all wind tunnel experiments. The upper surface of the element is only 0.010" wide (axial dimension), thus providing local force measurements in a streamwise direction, but it is 1.000" long (vertical dimension), so it will yield a measurable force. Figure 2 presents a 100 times scale drawing of the cross section of the tip of the model showing the element in the cavity. An oblique photograph of the element, the element suspension system showing the provision for two adjustments, and the top of the sting, is presented in Figure 3. A photograph of the entire skin friction apparatus, Figure 4, shows the model at the top, the circular adjustment plate directly below it, and the back side of the microbalance at the bottom. Since all cover plates have been removed, the sting which extends upward from the balance case and passes through clearance holes in the alignment devices can be seen in the recesses in the model. The element suspension is also visible but the element and cavity are too small to be seen clearly. A 6.5 times life size close-up of the element in the cavity and its suspension can be seen in Figure 5. The model installed in the wind tunnel with the floating element in place and the cover plates in position is shown in Figure 6. The Mach 6 nozzle can be seen to the left of the model. Figure 7 shows a view of the front side of the microbalance looking into the case through the access ports. The flexure pivot, balance beam, and quartz spring are visible; in addition the stops which limit the travel of the element in the cavity can be seen below the circular adjustment device.

The pressure instrumentation consisted of a thermistor pressure gage attached to the top of the model which was used to read the pressure in the model passage, a pressure line attached to the base of the model which was used to either outgas the model or to read the pressure in the entire apparatus with the aid of the precision oil manometer, and a pressure line attached to the base of the balance case which was used to control the pressure in the entire apparatus by bleeding a small quantity of air from the stagnation chamber.

Two special high stability mountings were constructed for the apparatus. One was a test bench with its foundation entirely separate from the remainder of the laboratory, and the other was a steel pedestal anchored to the wind tunnel foundation and protruding into the test chamber. Both were successful in providing a rigid and stable mounting which was also free of excessive vibration. The vacuum seal for the pedestal was accomplished by a separate external steel shell which incorporated two rubber couplings as vibration insulators.

III. RESULTS

For the calibration of the quartz spring and the subsequent wind tunnel tests the sensitivity of the microbalance was intentionally limited to a moderate and easily workable value so that these first exploratory tests would not be encumbered with the tediousness of extreme accuracy. The best value of the spring constant was 148.29 mg per inch, and without correcting for a small nonlinearity in the constant the probable error of the data was 0.18 mg per inch.

The first subject investigated after the apparatus was installed in the wind tunnel and working satisfactorily was the effect of cavity pressure on the indicated skin friction force. As was expected, the effect was considerable. The data are summarized in Table I under Run 733, and plotted in Figure 8. p_m/p_∞ is the ratio of pressure inside the model to the free stream static pressure and is used for its ready comparison with the induced pressure ratio, p/p_∞. The results of Run 733 indicate a 1%

change in p_m/p_∞ causes an approximate 1% change in the indicated skin friction. For these tests the accuracy of p_m/p_∞ was about 5%. The explanation for the variation of the indicated skin friction force with model pressure is relatively simple. Consider the case of the model pressure much lower than the induced surface pressure at the cavity location, and consider the element fixed in the center of the cavity. Air must flow around both sides of the element and then pass into the model through the clearances around the element suspension and sting. Figure 2 shows that the relief at the rear of the cavity allows p_m to act over nearly the entire rear surface of the element, while the small clearances below and at the front of the element result in an important pressure gradient in these regions. Thus the pressure distribution over a typical cross-section of the element causes a net force which adds to the skin friction force on the upper surface of the element. This force will be called the pressure error force. Now the suction taking place at the front and rear gaps, particularly the front gap, steepens the velocity gradient at the wall, and increases the indicated skin friction force. Since these two effects are additive, the indicated skin friction increases monatomically as p_m decreases. If p_m is much greater than the induced pressure at the cavity, the effects are just reversed in sign. With enough information about the local pressures in the cavity it would be a simple matter to correct for the pressure error force, so the main concern is with the alterations to the velocity gradient, since there will always be flow around the element, but very small gaps will significantly reduce this problem.

During Run 733 it was not possible to determine the induced pressure at the cavity because the flow passages around the element were too small to give reliable data. The element was removed and the model operated with the entire cavity acting as the pressure tap (Run 734). The results of these pressure model tests are presented in Table I and Figure 9. These results extend the range of the induced pressure data for sharp edged models taken in this laboratory (see Reference 2) from $\bar{\chi} = 10$ to $\bar{\chi} = 13$. The new data are in satisfactory agreement with the old data, even though the leading edge thickness was two orders of magnitude larger, and more importantly, both sets of data are in reasonable agreement with Aroesty's[8] first order slip correction to strong interaction theory (referred to as zeroth order theory). The estimated accuracy of p/p_∞ is 5%. These data were then used for the establishment of the proper p_m/p_∞ for the next sequence of force measurements, Run 735, and a repeat run, 736.

The results of the local skin friction measurements are given in Table I, and Figure 10. Three things are immediately obvious. The data are significantly below strong interaction theory, the repeatibility of the data is only fair, and the trend of the data with $\bar{\chi}$ is questionable. The values obtained for Run 736 are about 9% higher than Run 735, but this degree of uncertainty is small compared to the 25% disagreement of the general data level with strong interaction theory. The data strongly suggest that Aroesty's[8] slip correction underestimates the effect of slip, but the difference between the data and his prediction is just bordering on significance. It seems safe to judge that the continuation of the experiments will yield valuable and interesting data. The exact cause of the poor repeatibility is not known, but the best guess is that model pressure was incorrectly controlled because a leak existed at the model cover plate. An additional possibility which must be investigated in future tests is that extreme sensitivity to a geometric factor, such as the alignment of the element to the surface, caused a change in C_f. The existence of extreme sensitivity to small dimensional changes is illustrated by the following data obtained during Run 735. Figure 11 shows the indicated skin friction force was influenced by the position of the element in the cavity. The numbers (one unit = 5×10^{-5} inches) above the data points in the figure indicate the position of the element in the cavity at the time of the force reading. The displacement of the element represented by the two lines is 1.5×10^{-4} inches, or 4% of the total movement. This very small movement must have changed some geometric factor with resultant changes in the pressure error force and velocity gradient because the indicated force changed 0.8%. Incidentally, the slope of the lines indicates a 1% change in p_m/p_∞ caused a 0.94% change in the indicated force, which is in excellent agreement with the less precise data of Run 733. The very small scatter of the points obtained at the same element position shows the accuracy of the force measurement was 0.2%, which is quite creditable performance considering the microbalance was not adjusted for maximum sensitivity. Judging from the uniform shift between Runs 735 and 736, it would appear that the trend of $c_f \sqrt{\frac{Re_x}{C_\infty}}$ with $\bar{X}$ is repeatable. However, the validity of the trend is uncertain since Figure 12 shows the value of c_f for $\bar{X} = 9.8$ departs from the linear relation between the higher $\bar{X}$ data.

IV. CONCLUSIONS

1. The measured skin friction coefficients are significantly below the predictions of strong interaction theory and the existence of important slip effects is suggested but not precisely confirmed.

2. The performance of the microbalance was completely satisfactory, and no further refinements are anticipated.

3. Details of the model, particularly of the element and cavity, need further refinement.

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TABLE I. LOCAL SKIN FRICTION DATA SUMMARY

Run No.	Test Purpose	M	Re/in**	p_∞ μ Hg	q_∞ gm/cm^2	$\bar{X}$	F mg	C_f	$C_f\sqrt{\frac{Re_x}{c_\infty}}$	p_m/p_∞
733	Force vs p_m/p_∞	5.84	8540	102.5	3.33	10.50	14.8	-	1.32	5.90
							15.6	-	1.39	5.36
							16.2	-	1.44	5.10
							19.3	-	1.72	4.32
734	Pressure	5.94	10690	120.7	-	9.85	-	-	-	4.95
		5.85	8510	101.2	-	10.55	-	-	-	5.15
		5.70	6110	79.7	-	11.53	-	-	-	5.36
		5.56	4200	59.6	-	12.98	-	-	-	5.72
735	Force	5.95	10790	121.7	4.09	9.81	15.41	.0583	1.25	4.95*
		5.84	8500	101.7	3.31	10.52	15.34	.0719	1.36	5.15*
		5.69	6130	80.1	2.47	11.49	12.99	.0815	1.31	5.36*
		5.56	4280	60.7	1.78	12.93	10.95	.0951	1.26	5.72*
736	Force Repeat	5.53	3990	57.8	1.68	13.04	11.64	.1075	1.39	5.72*
		5.84	8540	102.3	3.30	10.50	16.51	.0775	1.47	5.15*

*Controlled to match values from Run 734

**The local x = 0.037". Re based on free stream values.

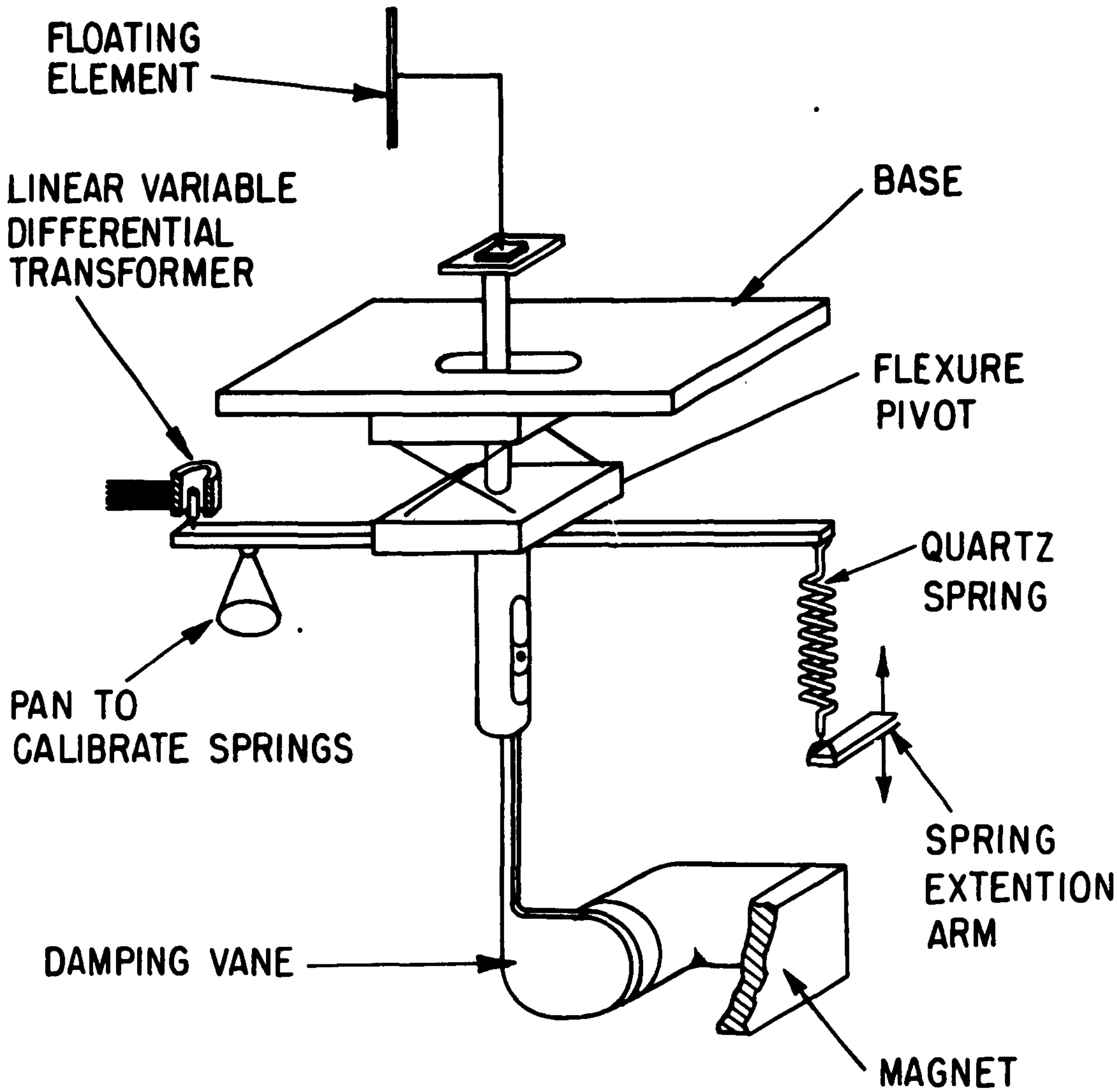

FIG.1 SCHEMATIC DIAGRAM OF BALANCE

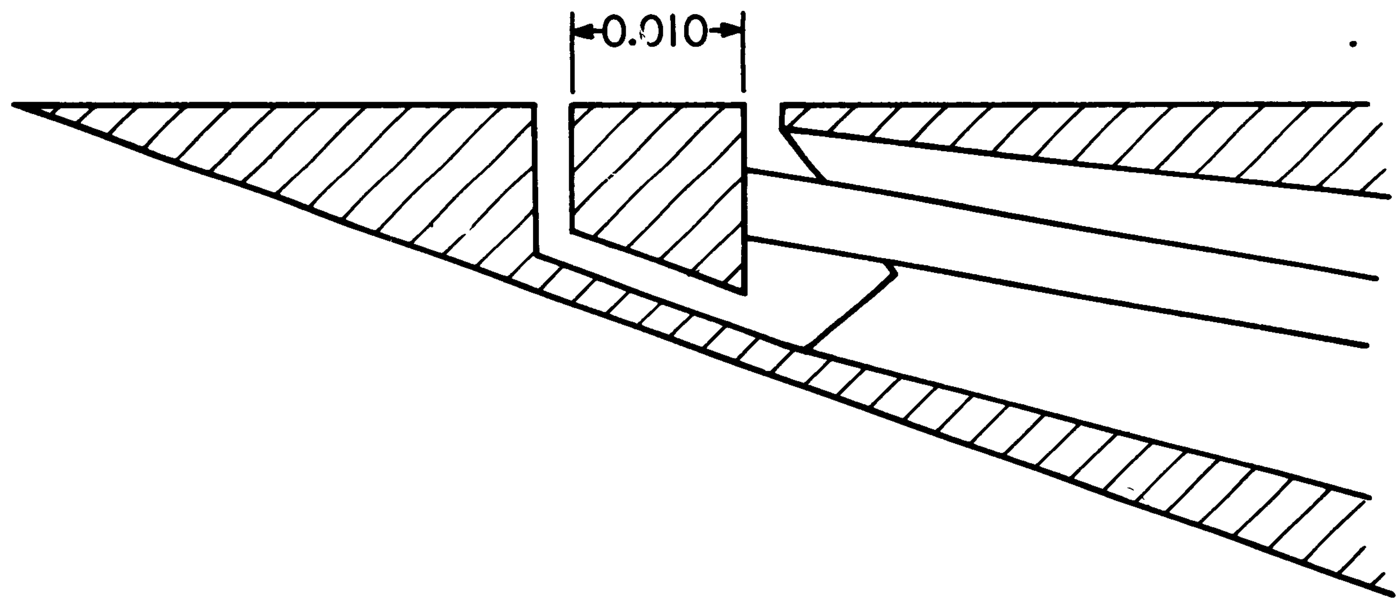

FIG. 2 CROSS SECTION OF MODEL TIP 100X

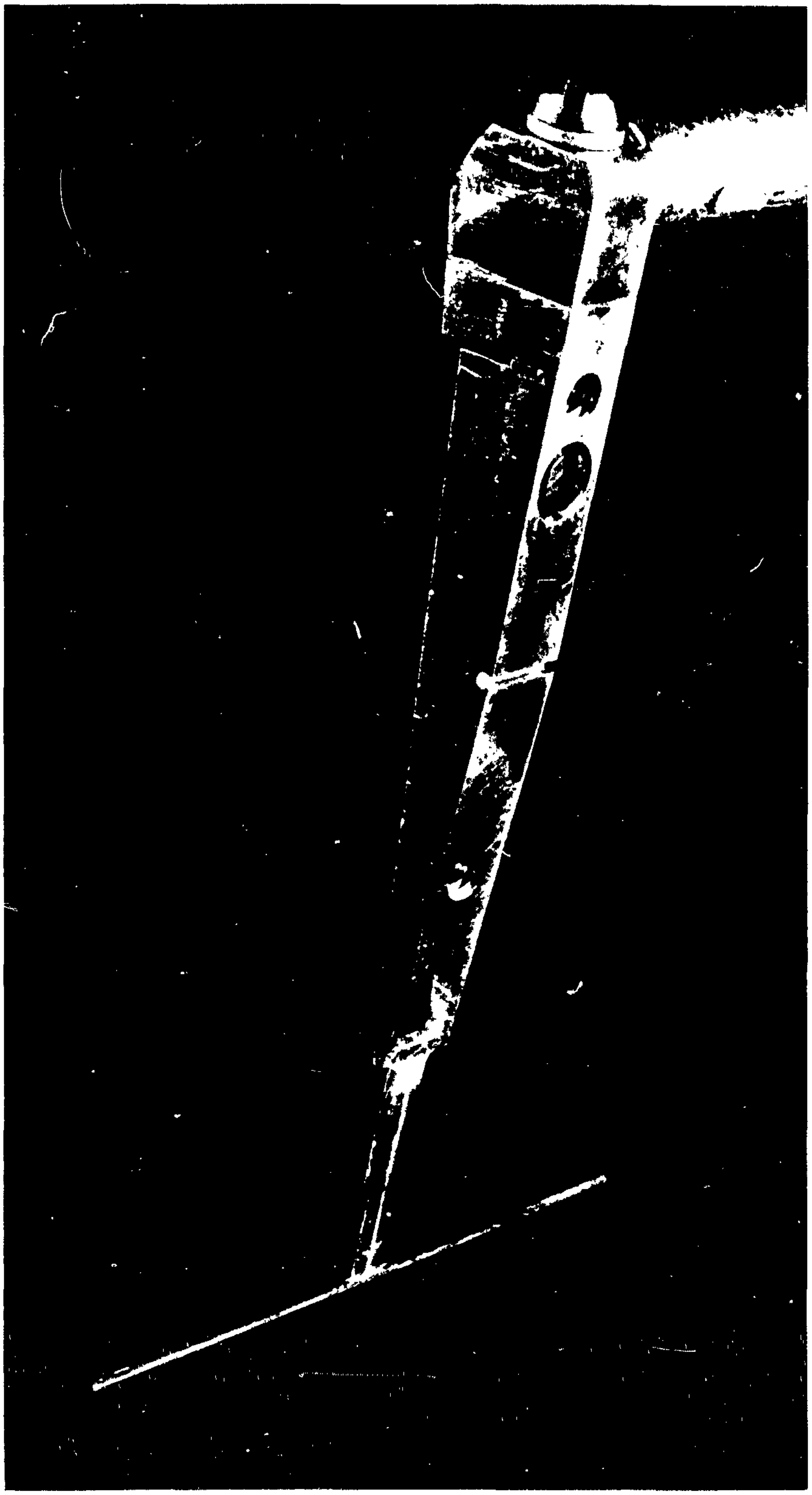

FIG. 3. ELEMENT AND ITS SUSPENSION

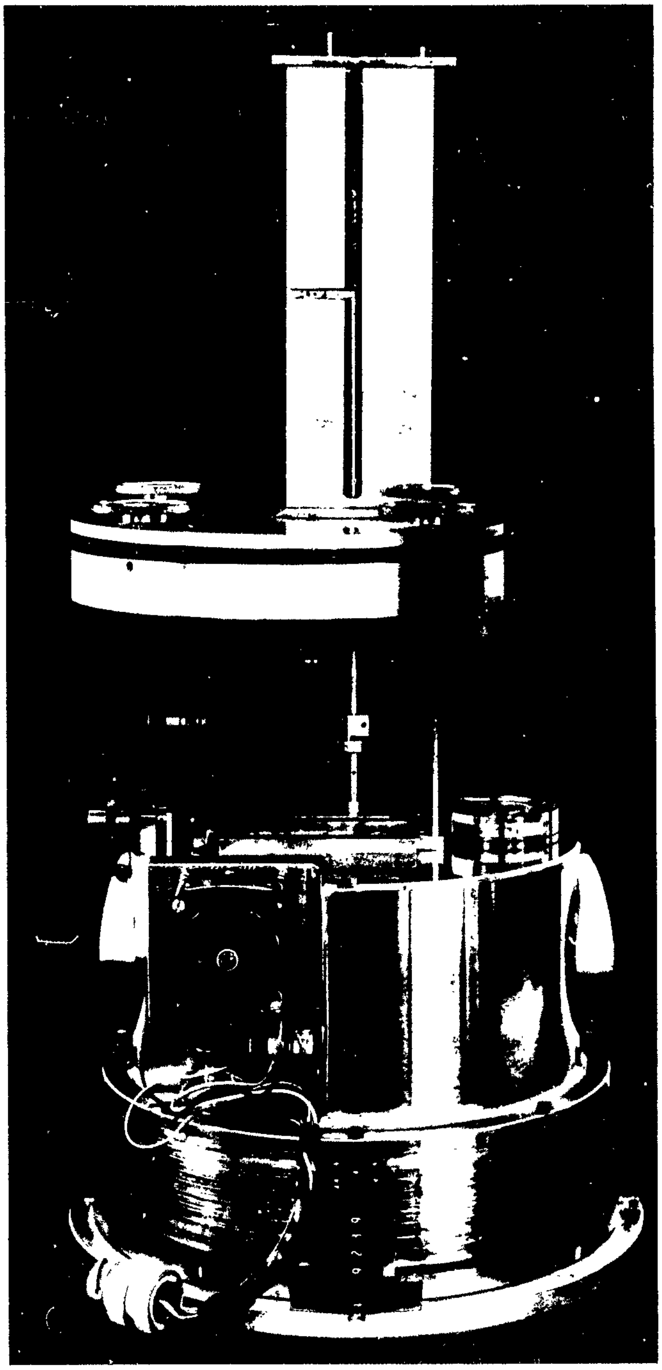

FIG. 4. LOCAL SKIN FRICTION APPARATUS
WITH ALL COVER PLATES REMOVED

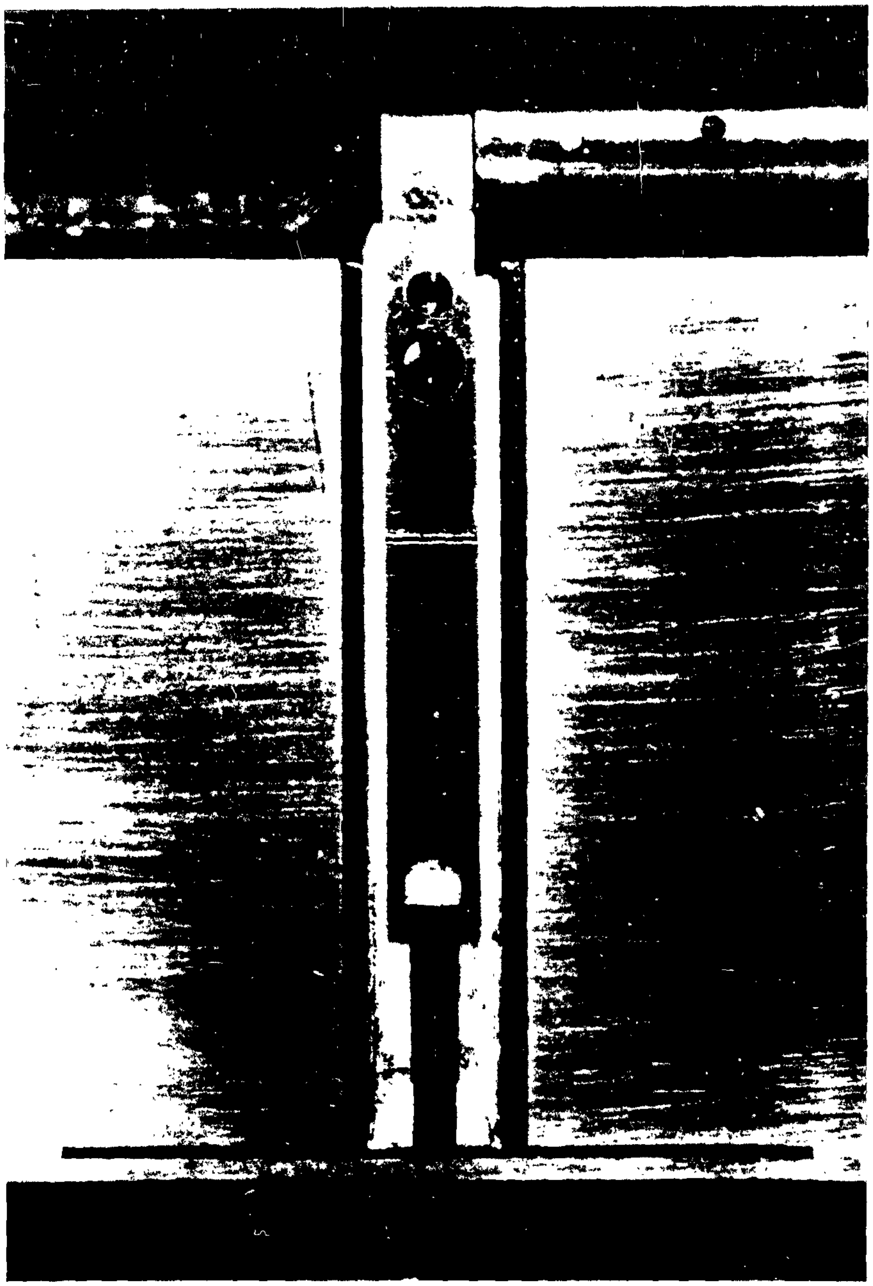

FIG. 5. ELEMENT IN MODEL CAVITY WITH COVER PLATES REMOVED 6.5 X

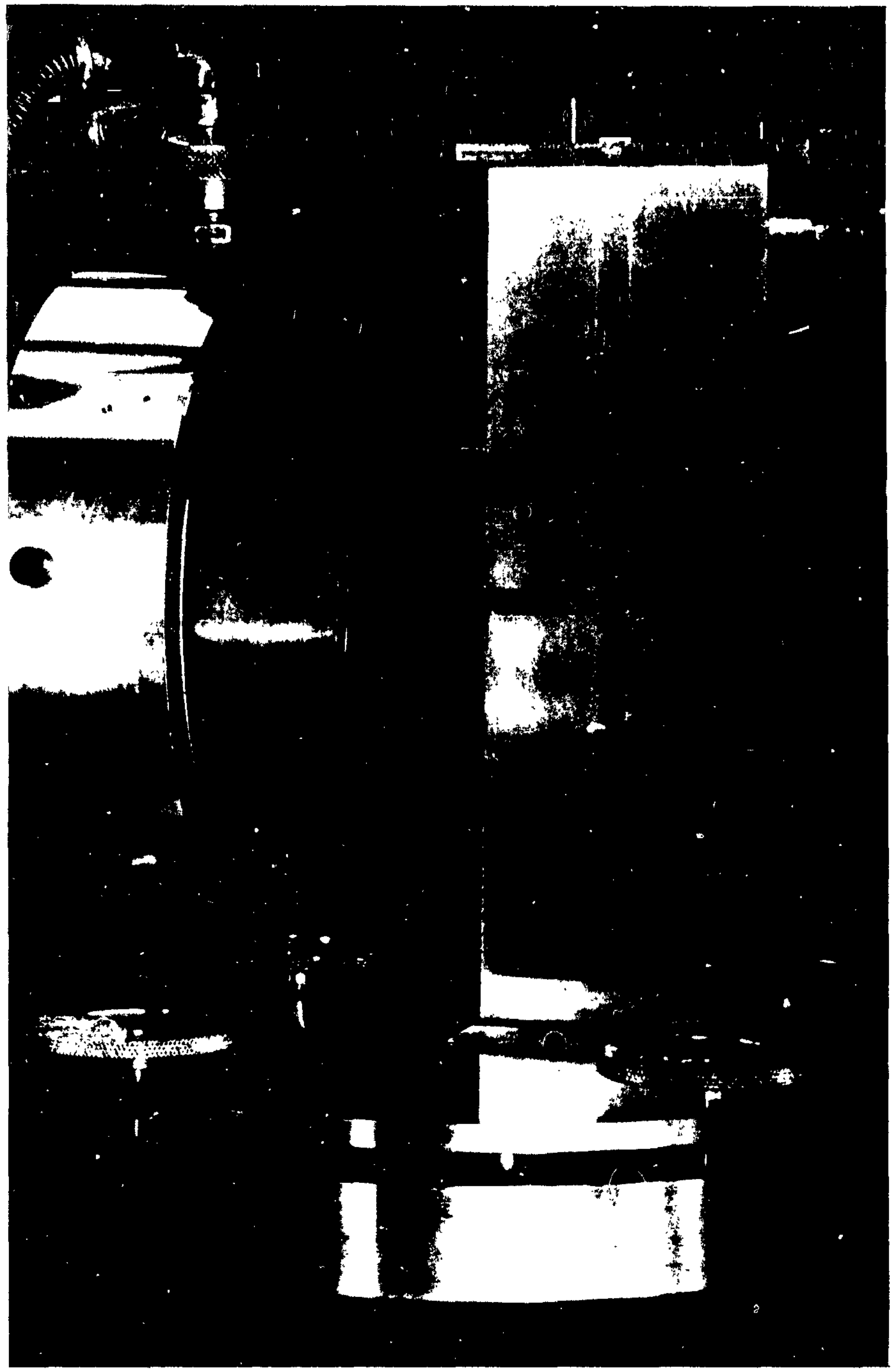

FIG. 6. MODEL IN FRONT OF MACH 6 NOZZLE
WITH COVER PLATES INSTALLED

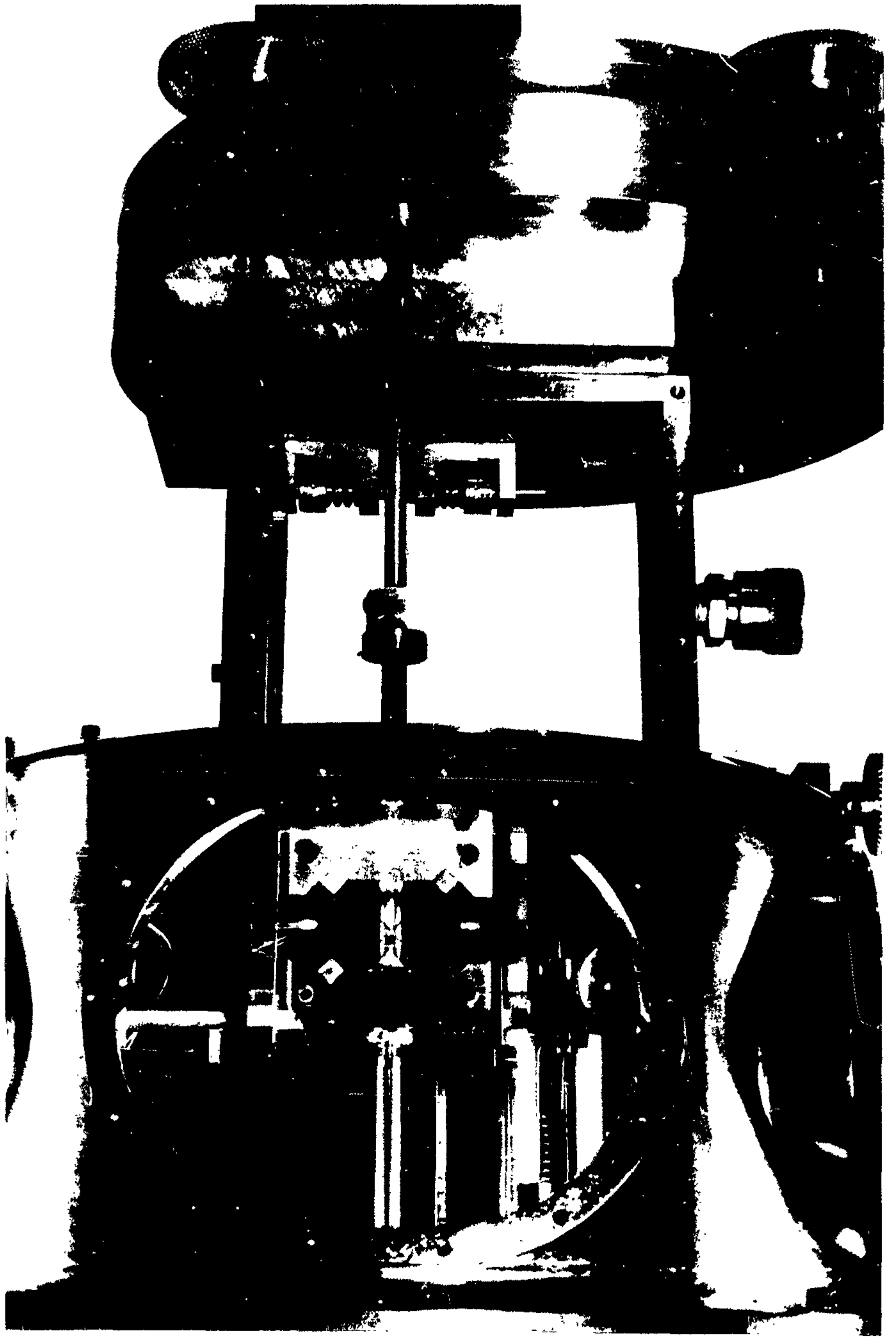

FIG. 7. INTERIOR OF MICROBALANCE

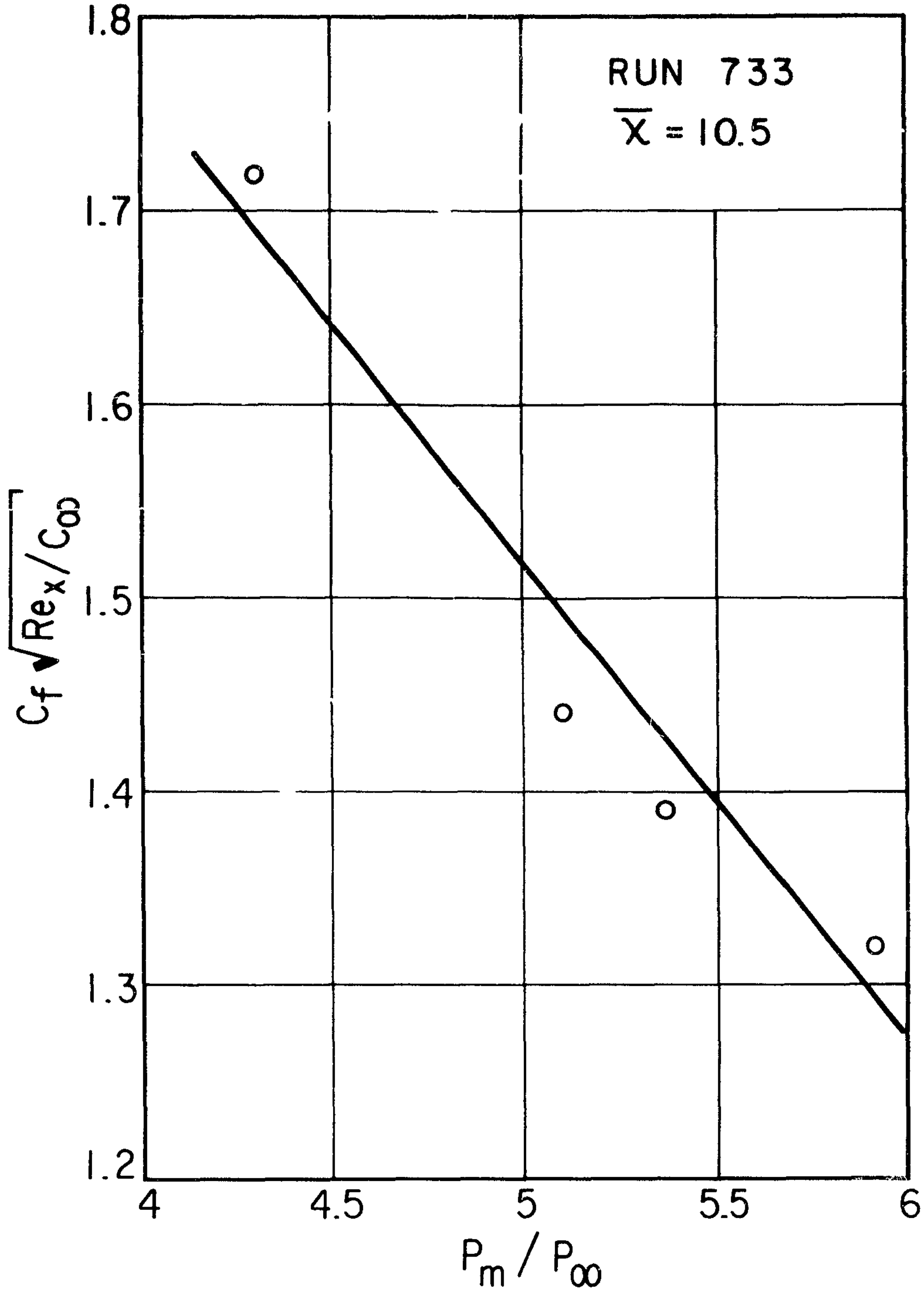

FIG. 8 INFLUENCE OF P_m/P_∞ ON SKIN FRICTION

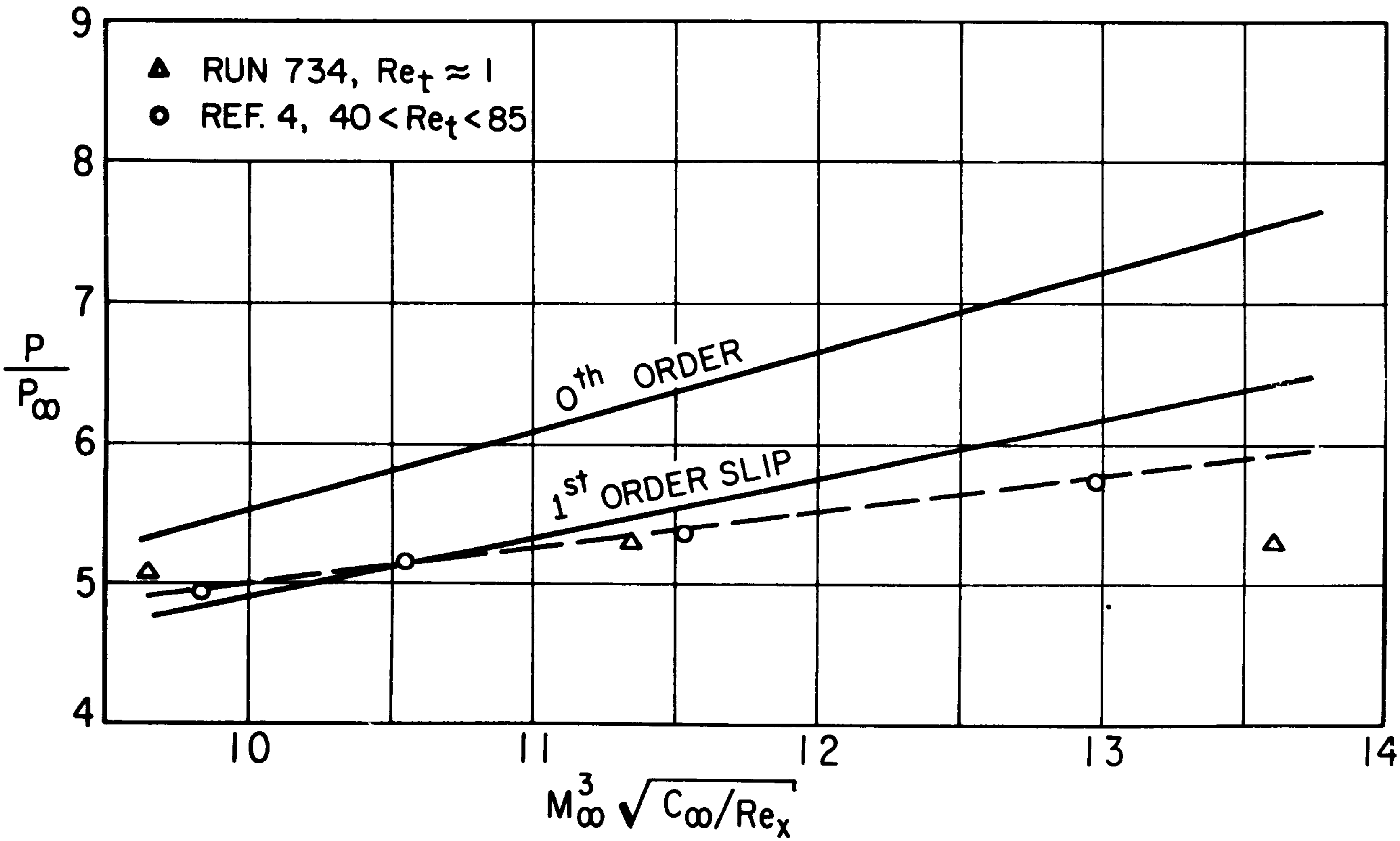

FIG. 9 INDUCED PRESSURE ON SHARP EDGED FLAT PLATES

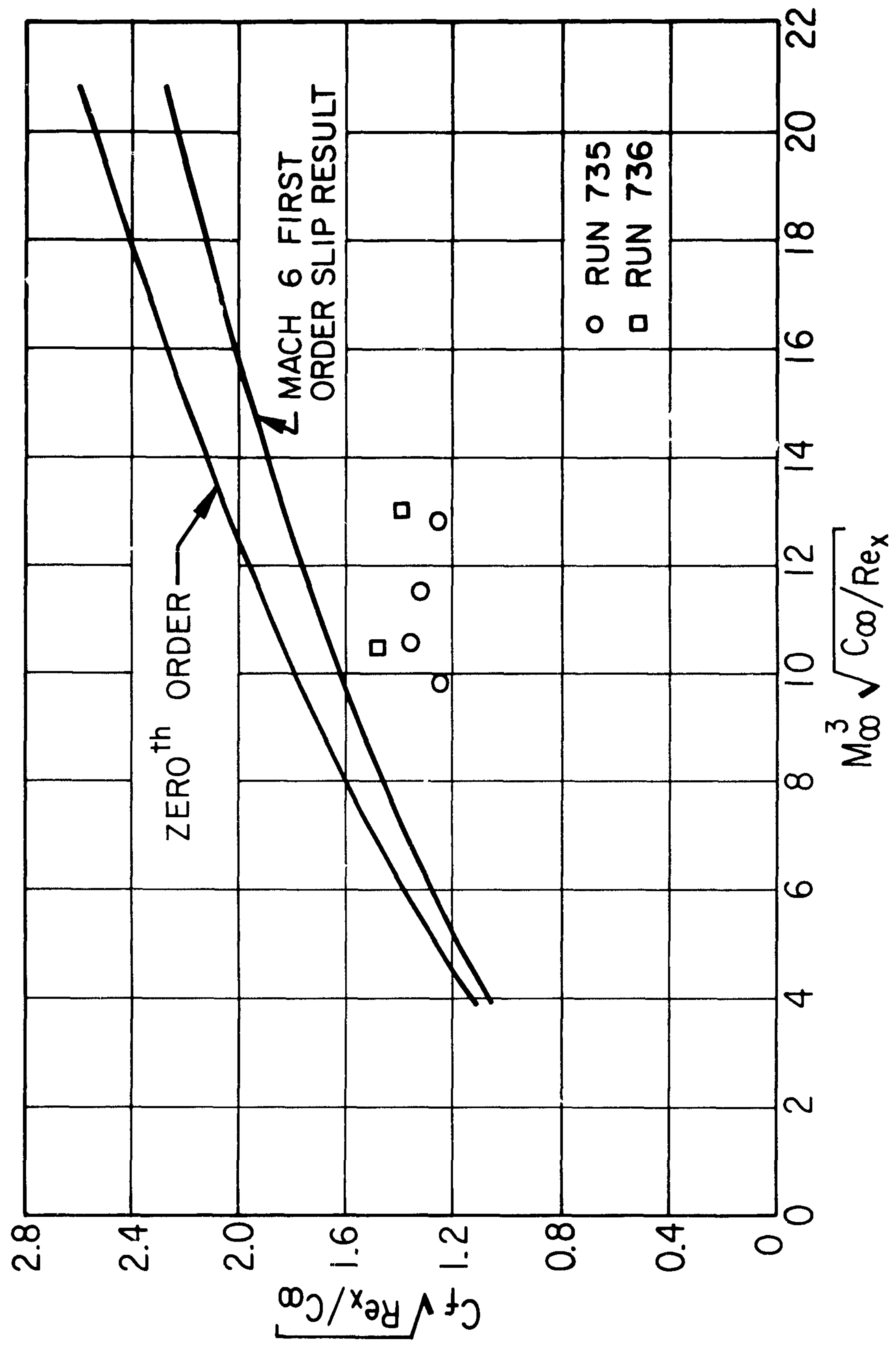

FIG. 10 SKIN FRICTION CORRELATION

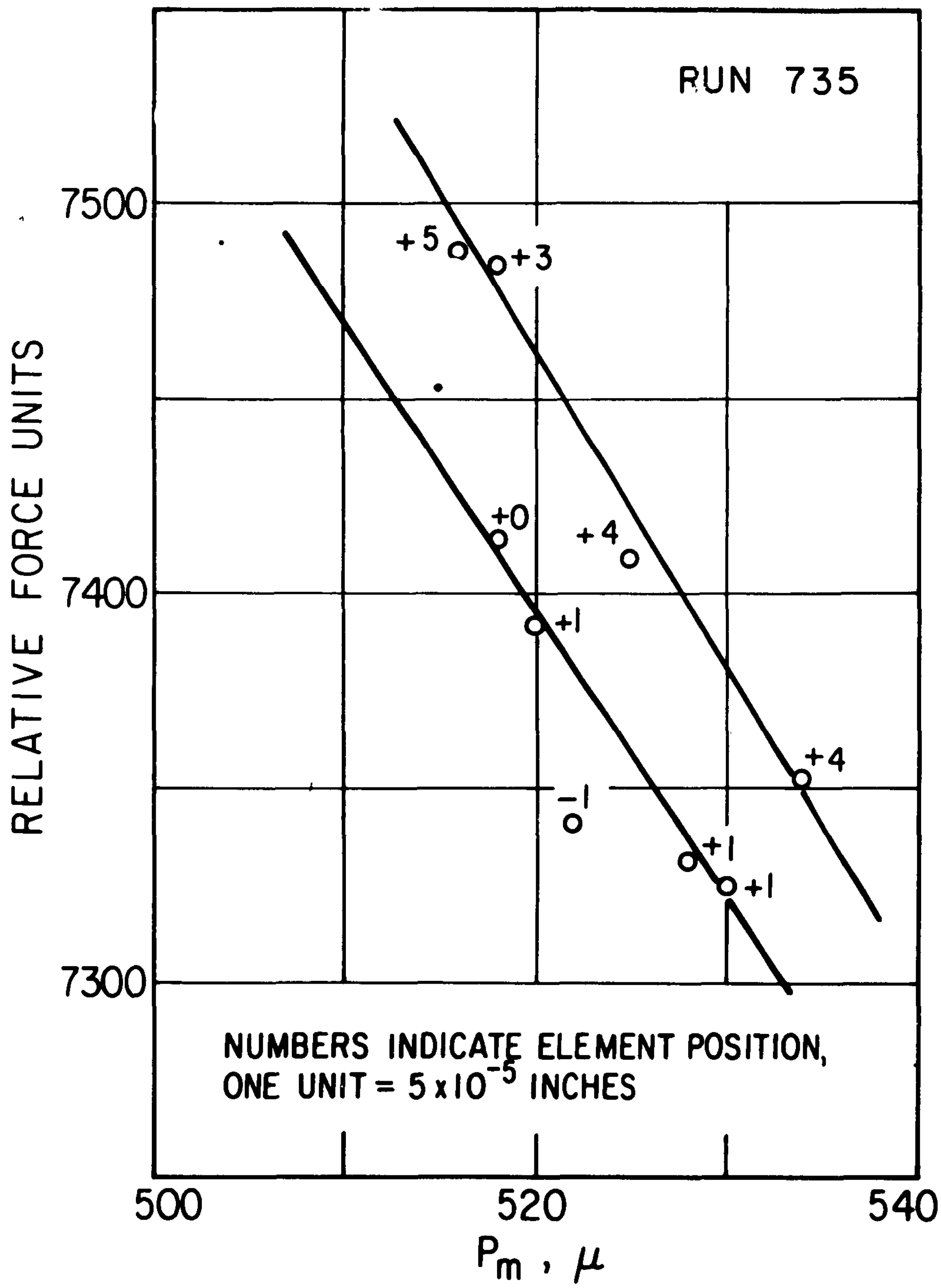

FIG. 11 INFLUENCE OF ELEMENT POSITION

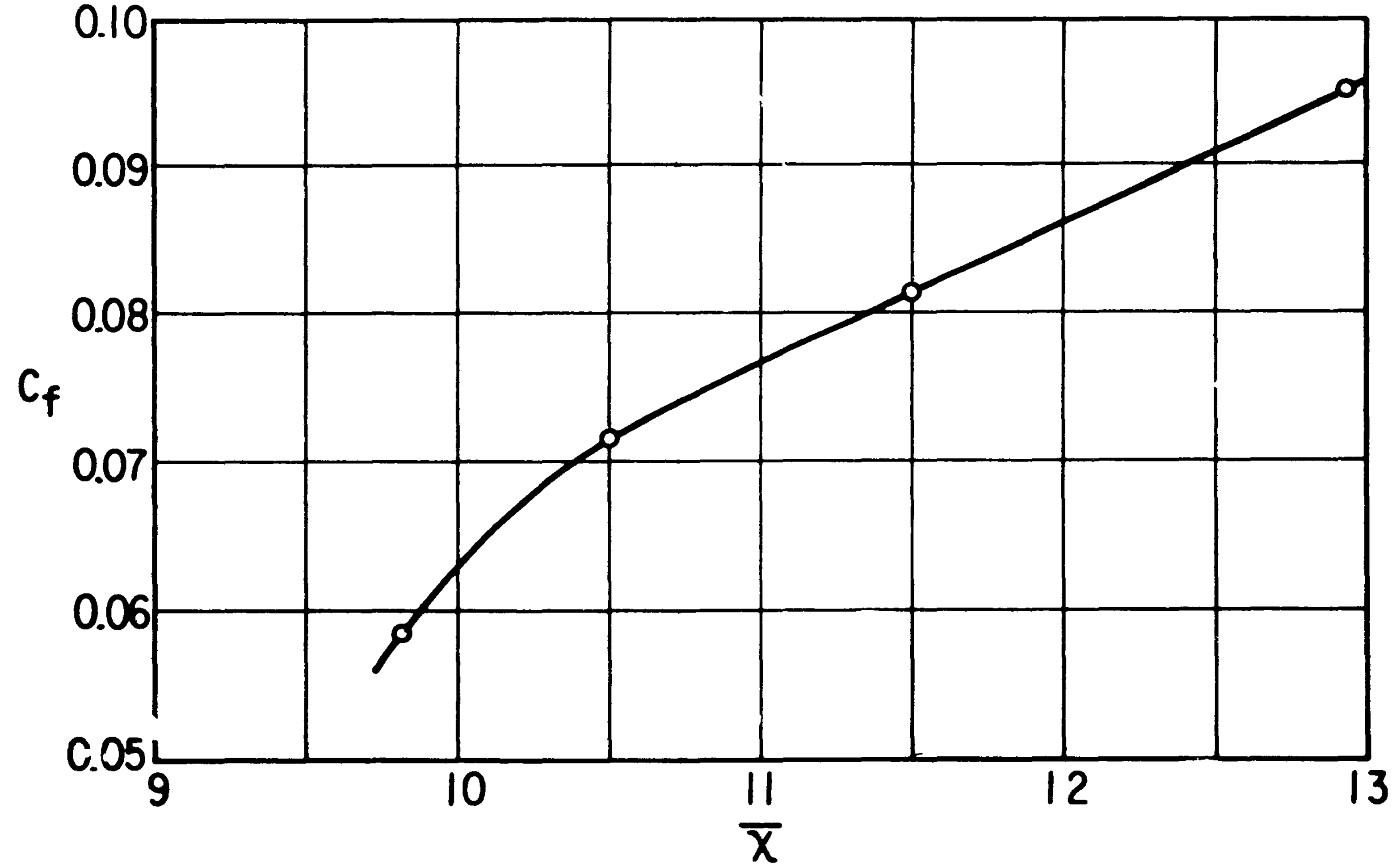

FIG. 12 SKIN FRICTION COEFFICIENT vs $\overline{X}$ FOR RUN 735

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